Exploiting the Spatio-Temporal Coherence of Ocean Ambient Noise for Passive Tomography

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LONG TERM GOALS

To develop passive modalities of acoustic ocean monitoring techniques such as acoustic tomography or acoustic thermometry using Cross-correlation processing of ocean ambient noise

OBJECTIVE

Extracting the coherent component of the ambient noise field propagating between a pair of passive receivers provides a means for passive acoustic sensing of the ocean environment. For instance, the arrival-times structure of the ambient noise cross-correlation time-function between a pair of receivers can yield an estimate of the arrival structure (or wavefronts) of the actual time-domain Green's function between these receivers, as if one of the passive receiver acted as an active source. Hence cross-correlation processing of ocean ambient noise has been suggested as a potential means for developing noise-based (or passive) modalities of acoustic ocean monitoring techniques such as acoustic tomography or acoustic thermometry

The main objective of this year research was to demonstrate that coherent arrivals can indeed be extracted from cross-correlations of very-low frequency ocean ambient noise (1 Hz $< f <$ 20 Hz) between pairs of hydrophones of the same hydroacoustic station located in the SOFAR channel of the Indian Ocean. The emergence rate of these coherent arrivals was determined in order to assess the feasibility of ocean basin scale (i.e. long range) passive tomography.

WORK COMPLETED

As part of the International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), a network of six underwater hydroacoustic stations has been deployed worldwide (see Fig. 1(a)). Each IMS hydroacoustic station uses one or two triangular horizontal arrays of three hydrophones, each side of the array being approximately 2 km long. For each array, the three hydrophones are nearly at the same depth within the ocean deep sound-channel (or SOFAR channel) primarily to allow for long-range detection of man-made (e.g. explosions) or natural (e.g. earthquakes) low-frequency hydroacoustic events [deGroot-Hedlin and Orcutt, 2001; Chapp et al, 2005; Gavrilov and Li, 2009]. Furthermore, continuously recording the deep water ocean noise provides a unique opportunity for passive monitoring of the ocean as well as environmental conditions in Antarctica [Gavrilov and Li, 2009; Prior et al., 2011].

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Previous studies of coherent processing of non-episodic ambient noise have typically been conducted at higher frequencies (f > 50 Hz), where the ambient noise is usually dominated by (diffuse) shipping noise: either in the Northern Pacific ocean of the California coastline [Roux 2004, Godin 2010] or in shallow coastal water [Sabra et al., 2005a; Fried et al., 2008; Siderius et al., 2010; Leroy et al., 2012]. The completed work demonstrates that coherent arrivals can indeed be extracted from cross-correlations of very-low frequency ocean ambient noise (1 Hz < f < 20 Hz) between pairs of hydrophones of the same hydroacoustic station in deep water.

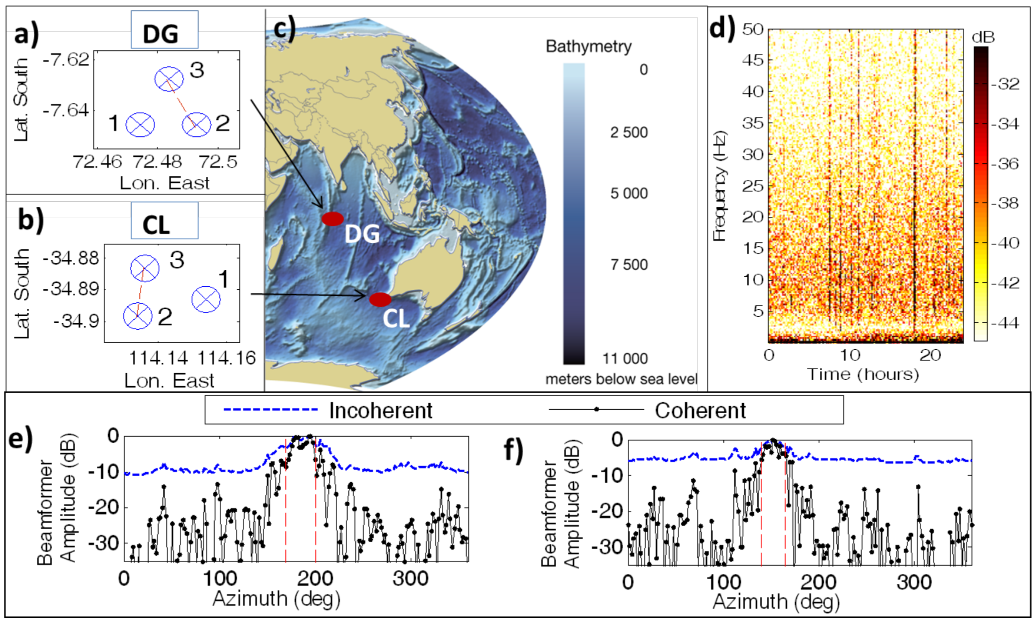

Fig. 1 Triangular configuration of the hydroacoustic stations DG (a) and CL (b). (c) Geographic location of DG and CL stations. (d) Spectrogram of the ambient noise recorded on the first hydrophone of CL station on 1/1/2006. Angular variations of the coherent (plain line) and incoherent (dashed lines) average over 130 days of the plane wave beamformer output (in the frequency band 1Hz-20Hz) for the hydroacoustic stations CL (e) and DG (f).

For reasons of data availability, this study focuses only on ambient noise recorded during 130 consecutive days (from January 1st to May 10th 2006) recorded by two hydroacoustic stations, labeled DG and CL hereafter, respectively located 1) south of Diego Garcia island (DG) and 2) south-west of Cape Leeuwin (CL), Australia (see Fig 1(a-c)). Ambient noise was recorded continuously Fig.1d. displays a typical spectrogram over a 24 hours recording period displaying three dominant features in agreement with previous studies [Gavrilov and Li, 2009; Prior et al., 2011]: (1) a very energetic narrowband and continuous component below 0.5 Hz due to ocean microseisms caused by nonlinear interactions between waves on the ocean surface, (2) a dominant frequency band of the ocean ambient noise ranging from 1 Hz (corresponding to the lower end of the bandpass filter automatically applied to the stored hydrophone data) up to ~20 Hz and (3) isolated transient events occurring at random instances (corresponding to vertical lines in the spectrogram). Previous seismic studies have already investigated the use and limitations of ocean miscroseisms for surface wave tomography across ocean basins [Lin et al., 2006]. The main interest of this letter is instead the intense very-low frequency

background component (1 Hz < f < 20 Hz) of the ambient noise field which occurred during the 130 day long analysis window, but not the episodic transient events. Consequently, to reduce the influence of high amplitude transient events while preserving the overall phase information of the time series, the noise recordings were homogenized using these two processing steps [Sabra et al. 2005b; Fried et al., 2008]: (1) whitening the amplitude spectrum of the data in the band [1 Hz- 20 Hz] to diminish strong spectral peaks and (2) clipping the signal amplitudes above a threshold equal to three times the average standard deviation of the whitened time series.

Given the frequency whitened and clipped time-series $S_i(t)$ and $S_j(t)$ recorded respectively by the i^{th} and j^{th} hydrophone of the selected triangular array (i,j=1..3) during the whole day k (k=1..130), the normalized cross-correlation function $C_{i,j}(t;k)$ for day k is defined by:

$$C_{ij}(t;k) = \int_{day\ k} S_i(\tau) S_j(\tau + t) d\tau \Big/ \sqrt{\int_{day\ k} S_i^2(\tau) d\tau} \Big/ \sqrt{\int_{day\ k} S_j^2(\tau) d\tau} \tag{1}$$

where t is the time delay (or time lag). The Fourier transform of each cross-correlation function for day k is denoted by $\hat{C}_{ij}(f;k)$ and corresponds to the entry (i,j) of cross-covariance matrix for the selected horizontal triangular array, denoted $\hat{\mathbf{C}}(f;k)$ at the frequency f. The output of the conventional plane-wave beamformer for a given steering azimuth θ can then be computed by [Siderius et al., 2010; Leroy et al., 2012]:

$$\hat{B}_k(f,\theta) = W^H(f,\theta)\hat{\mathbf{C}}(f;k)W(f,\theta) \tag{2}$$

where the symbol ^{H} denotes a complex transpose operation and $W(f,\theta)$ is the plane-wave steering vector towards a given azimuth θ (measured clockwise from the north direction). Furthermore when computing Eq. (2), the diagonal elements $\hat{C}_{ii}(f;k)$ (i=1..3) of the matrix $\hat{\mathbf{C}}(f;k)$ were set to zero to mitigate the bias due to electronic noise and the large incoherent component of the noise field [Westwood, 1992].

Figure 1(e-f) displays the maximum value of the coherent (or incoherent) average over 130 days of the time-domain beamformer $\sum_{k=1}^{130} B_k(t,\theta)$ (or $\sum_{k=1}^{130} |B_k(t,\theta)|$) as a function of the steering azimuth θ. The time-domain beamformer $B_k(t,\theta)$ for the k^{th} day of the 130 days analysis period is the inverse Fourier transform of beamformer $\hat{B}_k(f,\theta)$ -see Eq. (2)- across the frequency band [1 Hz-20 Hz]. The azimuths associated with the mainlobe of the beamformer output –approximately delimited by vertical dashed lines on Fig. 1(e-f) (155 deg-210 deg for CL station and 140 deg-165 deg for DG station) - appear to span the section of the Antarctica's coastline in the direct line of sight from these two hydroacoustic stations (see Fig. 1(a)). This spatial origin of the background ocean noise agrees with previous studies which demonstrated that most of the energetic events result from ice-breaking events in the vicinity of the Antarctica's coastline, especially during the Austral autumn (i.e. around the month of March) [Chapp et al., 2005, Gavrilov and Li, 2009; Prior et al., 2011].

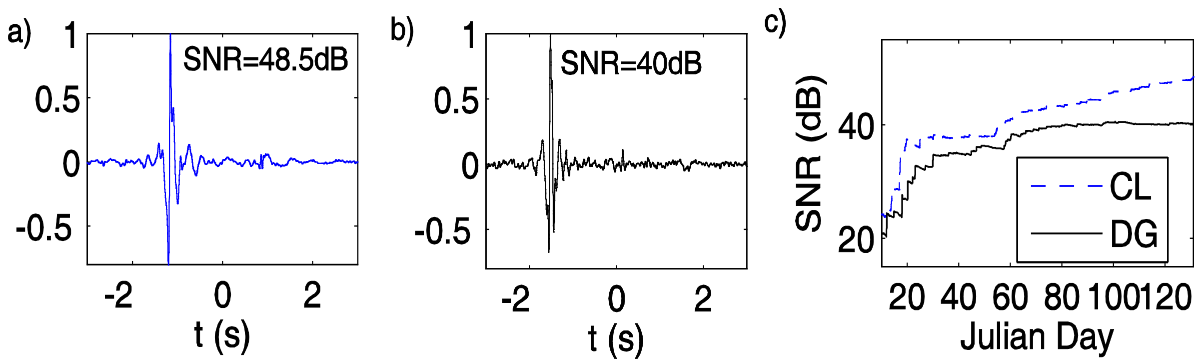

Fig. 2 ***Averaged cross-correlation waveforms*** $C_{av}(t, L=1; N=130)$ ***(see Eq. (1) and Eq. (3)) between hydrophones #2 and #3 (see Fig.1) obtained using a N=130 days long averaging for the hydroacoustic stations CL (a) and DG (b). Each waveform was normalized by its maximum value. (c) Evolution of the peak signal-to-noise ratio*** $SNR(L=1, N)$ ***of the cross-correlation waveform between hydrophones #2 and #3 (see Eq. (4)) for increasing number N of averaging day (N=1..130).***

The averaged cross-correlation waveform $C_{av}(t; L, N)$ is defined hereafter as the ensemble average of the daily cross-correlations $C_{i=2,j=3}(t;k)$, for hydrophone pair #2-#3 , between the days L and N of the analysis period (L$\leq$ k$\leq$ N):

$$C_{av}(t; L, N) = \sum_{k=L}^{N} C_{i=2,j=3}(t;k) \qquad (3)$$

This hydrophone pair #2-#3 was selected as it points South towards the Antarctica's coastline (see dashed lines on Fig 1(a-b))-i.e. towards the dominant origin of the coherent noise field for both CL and DG array (see Fig 1(c) and Fig. 1(e-f)). Figure 2(a) (or Fig. 2(b)) displays the averaged noise cross-correlation waveforms over all 130 days, i.e . $C_{av}(t; L=1, N=130)$ (see Eq. (3)), for both stations CL and DG. Each waveform exhibits a clear coherent arrival (for negative time delay only) whose arrival time is close to *L*/*c* where *L* is the separation distance of sensor #2-#3 (see Fig. 1(a)) and *c* is a reference sound speed value of 1485m/s typical for SOFAR channel in the Indian Ocean [Chapp et al., 2005]. The clear temporal asymmetry of the averaged correlation waveforms $C_{av}(t; L=1, N=130)$ confirms the dominant Southern origin of the ocean background noise recorded by DG and CL stations in the frequency band [1 Hz- 20 Hz] over the whole 130 days analysis period.

The peak signal-to-noise ratio of each averaged cross-correlation waveform is defined as the ratio of the peak value of the main coherent arrival of $C_{av}(t, L; N)$ (see Eq. (3)) to its standard deviation value at large time delays *t* where no coherent arrival is expected (selected here as the interval 1s < |t| < 2s) [Sabra et al., 2005b]:

$$SNR(L, N) = \frac{\max_t \{C_{av}(t, L, N)\}}{std\{C_{av}(1s < |t| < 2s, L, N\}} \qquad (4)$$

The standard deviation value is used here to estimate the level of residual temporal fluctuations of the cross-correlation waveform caused by the incoherent components of the noise field between the hydrophones #2 and #3 [Sabra et al., 2005b]. Fig. 2(c) compares the evolution of the signal-to-noise ratio $SNR(L=1,N)$ computed by averaging the cross-correlation waveforms across an increasing number of days N (N=1..130) for both DG and CL array. Note that actual value of the SNR is directly related to the azimuthal directionality of the time-domain beamformer output displayed on Fig. 2. Theoretically, this SNR should increase as $\sqrt{N}$ in the presence of a stationary and diffuse noise field [Sabra05b, Weaver05]. However both experimental SNR curves appear to deviate from this theoretical prediction of $\sqrt{N}$ and display instead a stair-step pattern, especially for CL array (see Fig 2.c). This indicates that the directional coherent noise field emanating from Antarctica's coastline was highly nonstationary during the analysis period, most likely due to the physical generation mechanism of ice-breaking events.

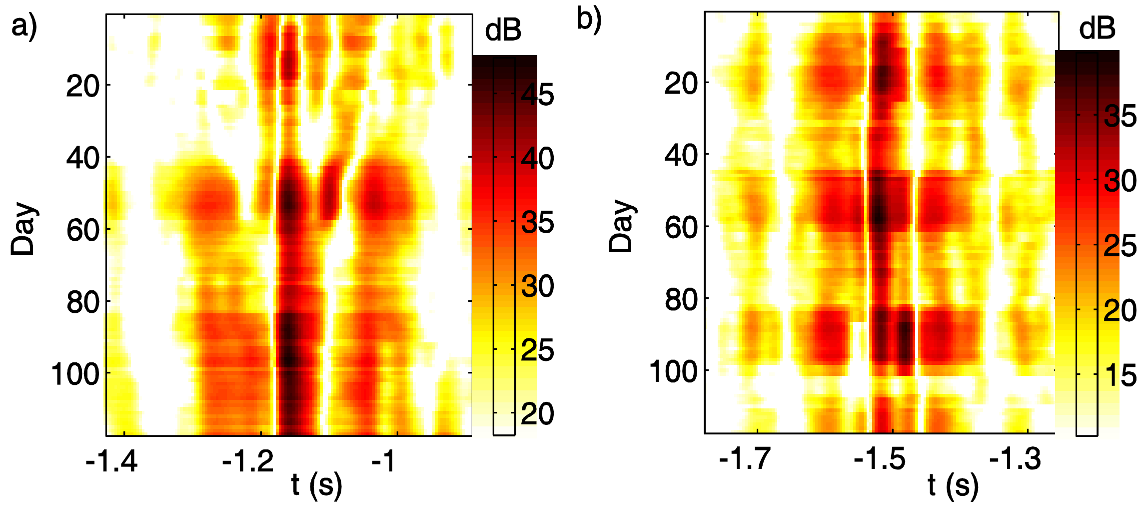

Fig. 3 ***Amplitude variations (in logarithmic scale) of the intensity of the noise correlation waveforms $C_{av}(t,N,N+15)$ between hydrophones #2 and #3 (see Fig. 1) computed using short moving average windows of 15days, starting on a variable day N across the whole 130 days observation period (1 ≤ N ≤ 115) for the hydroacoustic stations CL (a) and DG (b). Each correlation waveform $C_{av}(t,N,N+15)$ was normalized by the value of its standard deviation for the time-windows 1s < |t| < 2s; such that the maximum displayed value-in logarithmic scale-on each day N effectively displays the peak signal-to-noise ratio SNR(N,N+15) (see Eq. (4)) of the corresponding correlation waveform $C_{av}(t,N,N+15)$. Note that each plot has a different color scale.***

To confirm this interpretation, Fig. 3 displays the amplitude variations of the intensity of the stacked averaged correlation waveform $C_{av}(t,N,N+15)$ (see Eq. (3)) for both CL and DG hydroacoustic stations using short moving average windows of 15days, starting on a variable day N across the whole 130 days observation period (1 ≤ N ≤ 115). Furthermore, each stacked averaged cross-correlation waveform $C_{av}(t,N,N+15)$ was normalized by the value of its standard deviation for the

same window 1s<|t|<2s as previously used (i.e. $std\{C_{av}(1s<|t|<2s, N, N+15\}$). Consequently, for a given value of N along the vertical axis, the maximum values displayed on Fig. 3(a) and Fig. 3(b) directly correspond to the peak signal-to-noise ratio *SNR*(*N*,*N*+15) (see Eq. (4)) of the corresponding correlation waveform $C_{av}(t, N, N+15)$ displayed here using a logarithmic scale. Overall, Fig. 3(a) (or Fig. 3(b)) shows that the peak SNR values vary widely between 20dB and 45dB (or 20dB up and 40dB) for CL (or DG) station depending on the which 15 days interval is selected, thus confirming the nonstationarity of the flux of coherent noise propagating between hydrophones #2 and #3 over the whole 130 days observation period.

CONCLUSIONS

'The results of this research effort indicate that coherent arrivals can be extracted from coherent processing of low-frequency noise ([1Hz-20Hz]) emanating from the vicinity of the Antarctica's coastline. However, obtaining a consistent and relatively high SNR threshold (e.g. >20dB) for the main coherent arrival of the noise cross-correlation computed between a pair of hydrophones separated only by a short distance of L=2km requires at least several weeks of averaging. Assuming an ideal range and azimuth independent ocean as well as cylindrical spreading for these coherent arrivals propagating along the SOFAR channel, the coherent SNR (as defined in Eq. (4)) theoretically scales as a $\sqrt{T/L}$, where *T* denotes the total recording duration and L denotes the sensor separation distance [Roux et al., 2004]. Using this hypothetical scaling of the coherent SNR implies that achieving the same high SNR threshold value of 20dB for a large sensor separation distance of L=1000km could require several years of averaging in the best case scenario! Hence, the possibility of extracting persistent coherent noise arrivals between the CL and DG hydroacoustic stations located across the whole Indian Ocean using only a few months long moving average window (e.g. to perform noise-based acoustic thermometry with a sufficient temporal resolution) does not seem feasible given the present results.

IMPACT

It is conjectured that the results of this study could help develop a totally passive means for monitoring the ocean environment using only ambient noise. A potential scenario benefiting from the proposed methodology might include long-term deployment of ocean sensing systems requiring minimum power consumption, covert operations in hostile settings, or coastal deployments where active sources are limited by environmental regulations.

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